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# Magnetoresistive properties of exchange biased spin valve caused by helical magnetic ordering in dysprosium layer

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**Abstract.** Spin valves containing CoFe/Dy/CoFe nanostructure as a pinned layer were prepared by magnetron sputtering. Investigations of microstructure and magnetoresistive properties were performed. The magnetoresistive properties of the spin valve were used as the instrument to study the changes in magnetic state of the dysprosium layer. The existence of noncollinear magnetic ordering in dysprosium polycrystalline nanolayer was observed. The angle between the magnetic moments in a top and bottom part of the dysprosium layer was estimated.

## 1. Introduction

Bulk dysprosium is ferromagnetic below  $T_C = 85$  K, antiferromagnetic in the 85 - 179 K temperature range, and paramagnetic above the Neel temperature  $T_N = 179$  K. The Neel temperature for a dysprosium nanolayer in a nanostructure depends on its thickness and varies within 147 – 182 K [1]. Dysprosium has hexagonal close-packed (hcp) structure with a lattice parameters  $a = 0.3593$  nm and  $c = 0.5654$  nm. The [11-21] direction in the base plane corresponds to the easy magnetic axis (EA) [2]. The helical magnetic ordering is observed in dysprosium in the antiferromagnetic state. The magnetic moment in each base plane turns by an angle  $\alpha_0$  in relation to the magnetic moment in the neighboring base plane. In the  $T_C - T_N$  temperature range  $\alpha_0$  angle changes from 26.5 to 43.2° [3] and the step of the helical spiral changes from 4 to 2.5 nm [4].

In any nanostructure, the dysprosium layer is surrounded with layers of other magnetic materials. Such neighborhood is of greatest with an account for various magnetic types of ordering in the layers with 3d and 4f elements. Amorphous alloys can exist in the interface between layers of rare earth and transitional metals. The Curie temperature of such alloys may vary between 300 and 500 K. The coercive force of a Dy-Co-Fe alloy increases with decreasing temperature and reaches tens kilooersted [5]. These alloys contribute to magnetic properties of the nanostructure containing a layer of dysprosium [6].

In this work we investigate a microstructure and changes of a magnetic properties of a dysprosium layer which is a part of the FeMn-based spin valve. Magnetoresistive properties of such spin valve are



already rather well studied. Thus, we use the magnetoresistive properties of the spin valve as the instrument to study changes in magnetic state of the dysprosium layer.

## 2. Experiment

Spin valves of the Ta(5)/Ni<sub>80</sub>Fe<sub>20</sub>(2)/ Co<sub>90</sub>Fe<sub>10</sub>(3)/Cu(2.8)/Co<sub>90</sub>Fe<sub>10</sub>(3)/Dy(40)/Co<sub>90</sub>Fe<sub>10</sub>(2.5)/Fe<sub>50</sub>Mn<sub>50</sub>(10)/Ta(5) composition with Co<sub>90</sub>Fe<sub>10</sub>(3)/Dy(40)/Co<sub>90</sub>Fe<sub>10</sub>(2.5) pinned layer and three layered Co<sub>90</sub>Fe<sub>10</sub>(5)/Dy(40)/Co<sub>90</sub>Fe<sub>10</sub>(5) nanostructures were prepared by magnetron sputtering. Hereinafter thickness of layers are specified in brackets in nanometers.

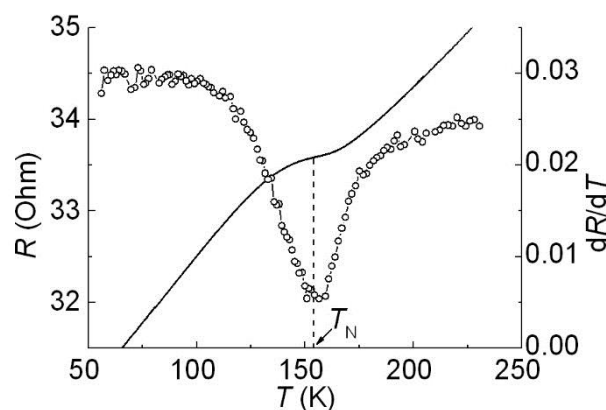
The microstructure was studied by X-ray diffraction using Co K $\alpha$  radiation and by transmission electron microscopy using the Tecnai G-30 electron microscope. For electron microscopy investigations the samples were thinned mechanically and subjected to ion milling.

The resistance was measured by dc four-probe technique in current-in-plane geometry using samples 2 mm  $\times$  8 mm in size. Copper contact pads were deposited using a mask. The magnetoresistance was determined as  $\Delta R/R_s = [(R(H) - R_s)/R_s] \times 100\%$ , where  $R(H)$  is the resistance of sample in a magnetic field and  $R_s$  is the resistance in the saturation field. The field and temperature dependences of resistance were measured in 23–293 K temperature range after cooling of the sample to 23 K in a magnetic field 9 kOe, applied along EA. The measurements were performed using a setup, which is assembled based on an electromagnet (Bruker), a flow cryostat, and a LakeShore 336 temperature controller.

## 3. Results and discussion

### 3.1. Estimation of Neel temperature and study of microstructure of dysprosium nanolayer

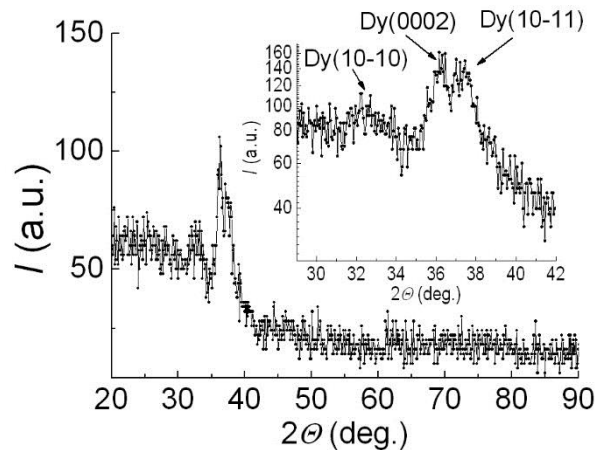
To estimate the dysprosium layer Neel temperature the dependence of resistance on temperature was measured for CoFe/Dy/CoFe nanostructure. The dependence is shown in figure 1. There is some inflection in  $R(T)$  curve. The inflection appears as the result of the transition of Dy from antiferromagnetic to paramagnetic state [6]. We calculated the derivative  $dR/dT$  and estimate  $T_N$  as it is shown in figure 1.



**Figure 1.** The resistance (line) and resistance derivative (symbols) on temperature dependence for CoFe/Dy/CoFe nanostructure.

For the dysprosium layer surrounded with CoFe layers  $T_N = 154$  K. Nominal thickness of the layer is 40 nm. We suppose that actual thickness of the dysprosium layer is less than 40 nm because of a diffusion in CoFe/Dy interfaces.

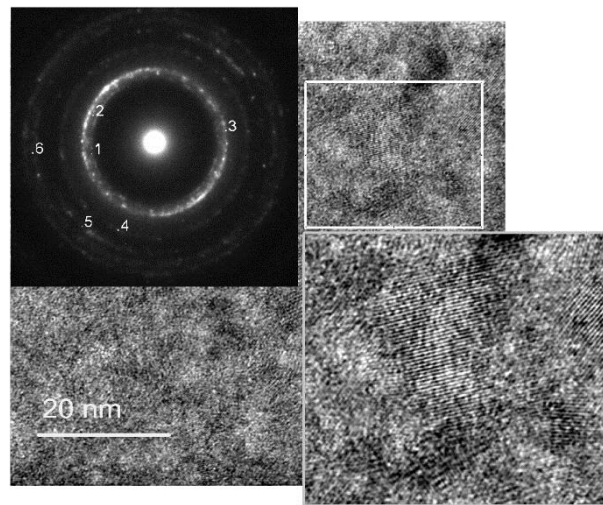
The results of X-ray investigation of CoFe/Dy/CoFe microstructure are shown in figure 2.



**Figure 2.** X-ray diffraction pattern of CoFe/Dy/CoFe.

There are three weak peaks of hcp lattice of dysprosium. Texture investigation reveals the imperfect  $\langle 0002 \rangle$  texture. Full width at half maximum (FWHM) of the rocking curve ( $\omega$ -scan) for (0002) peak is 19 degrees.

Figure 3 shows some results of TEM investigation of microstructure. The electron diffraction patterns



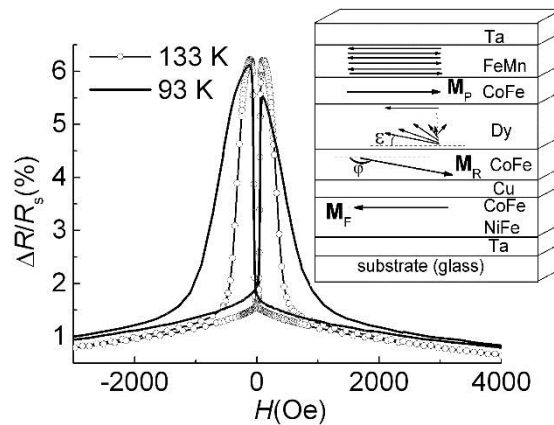
**Figure 3.** Electron diffraction pattern (left inset) and high-resolution image for CoFe/Dy/CoFe. Digits indicate Debye rings corresponding to 1 – Dy(10-10); 2 – Dy(0002); 3 – Dy(10-11); 4 – CoFe(111), Dy(10-12); 5 – Dy(11-20); 6 – Dy(10-13). The fragment selected by a rectangular frame is shown in an expanded scale.

show Debye rings corresponding to the hcp lattice of Dy and the fcc lattice of CoFe layers. The rings are continuous thus the orientation of crystal grains in a polycrystalline film is chaotic. The ring 3 is surrounded with diffuse glow. Its emergence can be caused by formation of intermetallic compounds in the Dy/CoFe interfaces. In high-resolution image, one can see straight thin parallel lines. It is the atomic plane projections in the image plane. The spacing between the lines is  $d = 3.1 \text{ \AA}$ , which corresponds to the spacing between (10-10) planes of Dy. Thus, there are areas in Dy layer in which

[0002] direction is perpendicular to the film plane, and the basic plane of hcp lattice lies in the film plane.

### 3.2. Magnetotransport properties of the spin valve containing a dysprosium layer

The studied nanostructure is the spin valve in which the ferromagnetic (CoFe) layer adjacent to the antiferromagnetic one (FeMn) is separated by a Dy layer into two parts hereafter referred to as pinned and reference layers. The layers of the spin valve and the magnetic moments  $\mathbf{M}_p$ ,  $\mathbf{M}_R$  and  $\mathbf{M}_F$  of pinned, reference and free layers as well as magnetic moments in dysprosium layer at antiferromagnetic state are shown in the inset in figure 4. The magnetoresistive curves were measured at fixed temperatures from 23 – 293 K in the field  $H$  applied parallel to easy axis (EA) of the spin valve. The curves were symmetric at  $T \geq 133$  K and asymmetric at  $T < 133$  K. Figure 4 shows the magnetoresistive curves measured at 133 and 93 K.

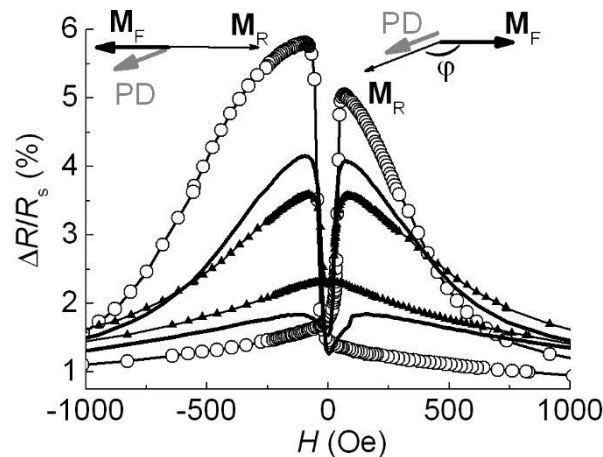


**Figure 4.** Field dependencies of magnetoresistance measured at temperatures 93 and 133 K for Ta(5)/NiFe(2)/CoFe(3)/Cu(2.8)/CoFe(3)/Dy(40)/CoFe(2.5)/FeMn(10)/Ta(5) spin valve. The inset shows the layers of the spin valve, the magnetic moments of free, pinned and reference layers and magnetic moments inside dysprosium layer in antiferromagnetic state.

At  $T \geq 133$  K the  $\Delta R/R_s(H)$  dependences have no features of an unidirectional anisotropy which is formed in the FeMn/CoFe interface. We suppose the reason is in paramagnetic state of the dysprosium layer. At  $T < 133$  K the Dy layer is antiferromagnetic. The difference in maximal magnetoresistance in positive and the negative fields ( $(\Delta R/R_s)_{\max}(+)$  and  $(\Delta R/R_s)_{\max}(-)$ ) appears as the result of unidirectional anisotropy and forming pinning direction (PD) in the reference layer. Let us note that in the pinned layer  $PD \parallel EA$ , but in the reference layer PD deviates from EA. It is important, that  $(\Delta R/R_s)_{\max}(+) < (\Delta R/R_s)_{\max}(-)$ , if we perform the magnetoresistive measurements in the field  $H$  which is parallel to the field applied upon cooling the sample ( $H_{\text{cool}}$ ). If we deviate  $H$  from  $H_{\text{cool}}$  by some angle the difference between  $(\Delta R/R_s)_{\max}(+)$  and  $(\Delta R/R_s)_{\max}(-)$  decrease. Then  $(\Delta R/R_s)_{\max}(+) = (\Delta R/R_s)_{\max}(-)$  if we measure the magnetoresistive curve at  $H \perp H_{\text{cool}}$  (figure 5). If we change  $H_{\text{cool}}$  field direction the regularity remains unchanged, that is at  $H \parallel H_{\text{cool}}$  magnetoresistance curve is asymmetrical and at  $H \perp H_{\text{cool}}$  it is symmetrical relative to  $H = 0$ .

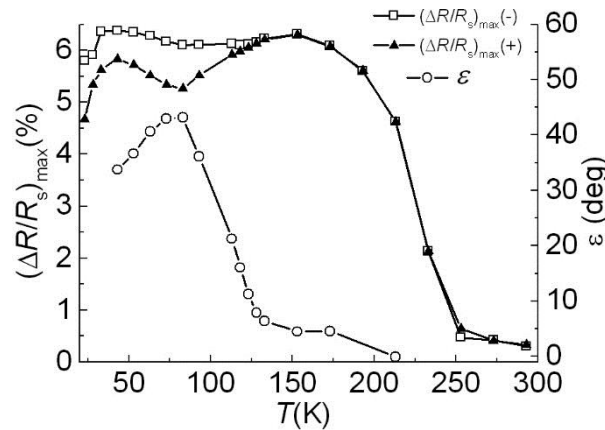
Estimated Neel temperature for the dysprosium layer is 154 K. Thus, at  $T < 133$  K full antiferromagnetic ordering was created in dysprosium layer and this ordering is noncollinear.  $\mathbf{M}_p$  is

coupled antiferromagnetically to the magnetic moment of the upper part of the dysprosium layer in the same way as  $\mathbf{M}_R$  to the magnetic moment of the bottom part of Dy layer (see the inset in figure 3). There is the rotation of the magnetic moment in the Dy layer. Determination of the angle between  $\mathbf{M}_P$  and  $\mathbf{M}_R$  permits us to estimate the angle between the magnetic moment of the upper part of the dysprosium layer and the bottom one. Mutual orientation of  $\mathbf{M}_R$ ,  $\mathbf{M}_F$  and PD at the magnetoresistance maximum in positive and negative fields is shown schematically in the insets in figure 5.



**Figure 5.** Field dependencies of magnetoresistance measured at the field  $H$  which was applied at 0 (light symbols), 60 (line) and 90 (dark symbols) degrees relative  $H_{cool}$ . The left and right insets show orientations of pinning direction and magnetic moments of free and reference layers corresponding to the maximum magnetoresistance in the negative and positive fields.

In the negative fields  $\mathbf{M}_R$  deviates from PD due to the large coercive force at the Co-Fe-Dy interface. The angle  $\varphi$  between  $\mathbf{M}_R$  and  $\mathbf{M}_F$  is  $180^\circ$ . In the small positive fields  $\mathbf{M}_R \parallel \text{PD}$ . The coercivity of Co-Fe-Dy is not an obstacle in this case since the sign of  $\mathbf{M}_R$  projection to  $H$  does not change. As a result,  $\varphi < 180^\circ$ , and thus  $(\Delta R/R_s)_{\max(+)} < (\Delta R/R_s)_{\max(-)}$ . Figure 6 shows the temperature dependences of maximum magnetoresistance of the spin valve measured in the positive and negative fields.



**Figure 6.** Temperature dependencies of maximum magnetoresistance  $(\Delta R/R_s)_{\max}(-)$  and  $(\Delta R/R_s)_{\max}(+)$  measured in the positive and negative fields and temperature dependence of  $\varepsilon$  angle between magnetizations of the top and the bottom part of the dysprosium layer.

Considering the existence of helical ordering in Dy layer in the 43 – 133 K temperatures, we calculate the angle  $\varphi$  and estimate the angle  $\varepsilon$  between the magnetic moments in upper and the bottom part of Dy layer (the inset in figure 4) as follows.

### 3.3. Estimation of the angle between the magnetic moments in upper and the bottom part of Dy layer

The direction of the magnetic moment in the bottom part of Dy layer is defined by a phase of a helicoidal spiral.  $\mathbf{M}_R$  is exchange biased with this direction, while the direction of the magnetic moment in the bottom part of Dy layer is exchange biased with  $\mathbf{M}_P$  and parallel to EA in small fields. Thus monitoring of the  $(\Delta R/R_s)_{\max}$  value permits to estimate the  $\varphi$  and  $\varepsilon$  angles. The value of magnetoresistance depends on the angle  $\varphi$  between  $\mathbf{M}_R$  and  $\mathbf{M}_F$ .

The resistance of a spin valve is described by the expression

$$R(\varphi) = R_P + (R_{AP} - R_P)(1 - \cos\varphi)/2 \quad (1),$$

where  $R_P$  and  $R_{AP}$  are the resistances of spin valve at parallel and antiparallel position of  $\mathbf{M}_r$  and  $\mathbf{M}_f$  [7]. Assuming that  $R_P$  is the resistance in the saturation field,  $(R(\varphi) - R_P)/R_P = (\Delta R/R_s)_{\max}(+)$  and  $(R_{AP} - R_P)/R_P = (\Delta R/R_s)_{\max}(-)$  we obtain:

$$\cos(\varphi) = 1 - 2(\Delta R/R_s)_{\max}(+)/(\Delta R/R_s)_{\max}(-) \quad (2)$$

$(\Delta R/R_s)_{\max}(-)$  and  $(\Delta R/R_s)_{\max}(+)$  values were measured for the magnetoresistive curves and the angles  $\varphi$  and  $\varepsilon = 180 - \varphi$  were estimated.

Figure 6 shows the temperature dependence of the  $\varepsilon$  angle. It is close to zero at  $T \geq 153$  K. At 153 – 133 K the  $\varepsilon$  angle begins to grow. It will well be coordinated with measured Neel temperature  $T_N = 154$  K (figure 1). Then the decrease of temperature is accompanied with change of the  $\varepsilon$  angle. It increases from 8 to 43 and then decreases to 33 degrees. The reason of these variations is the dependence of the helicoidal spiral step on the temperature.

The performed estimations is true for those crystallites of dysprosium polycrystalline film where [0002] direction is perpendicular to the film plane. According to the electron and X-ray diffraction investigations, such areas exist in the investigated samples. They are seen in the high-resolution images (figure 3).

## 4. Conclusion

According to the temperature dependencies of resistance of CoFe/Dy/CoFe nanostructures, the Neel temperature for the dysprosium layer with thickness 40 nm is  $T_N = 154$  K.

Using the magnetoresistive properties of spin valve as a measuring instrument we observed the existence of noncollinear magnetic ordering in dysprosium polycrystalline nanolayer and estimated the values of the angle between the magnetic moments at top and bottom of the dysprosium layer.

The structural investigations show that the dysprosium nanolayer surrounded by CoFe alloy layer is polycrystalline and has very weak  $\langle 0002 \rangle$  texture. Nevertheless, the changes of magnetotransport properties of the spin valve permitted us to assume that a noncollinear helical magnetic structure is formed in the dysprosium layer.

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